WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

Field of the Invention

The present invention relates broadly to a high optical confinement waveguide structure and a method for forming the same.

Background of the Invention

High confinement optical waveguides rely on a high refractive index contrast between the waveguide material and surrounding cladding material/optically isolating layers. This allows the design of very compact waveguide structures, which have found numerous applications enabling dramatic reduction in device dimensions while maintaining the required optical functionality.

Recently, silicon has been identified as a suitable material for the production of high confinement waveguide structures. Silicon has a high refractive index of the order of 4 at 1.5 micro meter wavelength. High confinement optical waveguides based on silicon as the waveguide material are presently manufactured utilising a technique known as "Separation by Implanted Oxygen" (SIMOX) to create Silicon on Insulator (SOI) structures. In the SIMOX technique oxygen is implanted into a silicon wafer. The wafer is then annealed to form a silicon layer above a layer of oxidised silicon formed from the implanted oxygen at a predetermined implantation depth.

However, this technique suffers from several disadvantages including the high cost related to the complex fabrication of SIMOX substrates, and the limited range of variations in the parameters of the SIMOX substrates, such as the limited range of the waveguide material properties (bulk silicon) and the limited range

of achievable thicknesses of the oxidised optical isolation layer created through oxygen implantation.

Summary of the Invention

The present invention provides a method for forming a high optical confinement waveguide structure. The method comprises the step of forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate, wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

Accordingly, thin film technology can be used to fabricate high optical confinement silicon-based waveguide structures, which can increase the range of properties of the silicon-based waveguide of the waveguide structure.

The method may further comprise the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer. The wafer may comprise a silicon wafer. The first layer may be silica-based.

The forming of the silicon-based waveguide may further comprise etching the deposited waveguide layer. The etching may be performed in a manner such as to form a ridge structure in the deposited waveguide layer. The method may further comprise the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure. Accordingly, the height of the ridge structure can be more accurately controlled compared to relying on uniformity of the etching process.

The method may further comprise the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide. The step

of varying the refractive index may comprise exposing the deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

The silicon containing material may comprise a dopant material.

The silicon containing material may be selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

The silicon containing material may be selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

The method may further comprise crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer. The step of crystallising may comprise utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the first material to control a grain size in the crystallised waveguide.

The step of forming the waveguide may comprise plasma enhanced chemical vapour deposition (PECVD).

The step of forming the waveguide may comprise forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre. The step of forming the taper may comprise varying the refractive index of the deposited waveguide layer in the end portion of the waveguide. The varying of the refractive index in the end portion may comprise controlled oxidation of the deposited waveguide layer. The controlled oxidation may comprise a laser to heat the deposited waveguide layer. The laser may comprise a CO_2 laser.

The method may further comprise the step of forming a processing element in and integrated with the deposited waveguide layer.

The present invention may alternatively be defined as providing an optical device incorporating a silicon-based waveguide structure formed on a substrate, and a processing element formed and integrated with the silicon-based waveguide structure.

The processing element may comprise a photodetector incorporating a dopant material in the silicon-based waveguide structure.

The present invention may alternatively be defined as providing a method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of oxidising the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling, wherein the oxidising is controlled in a manner such that a refractive index profile is created in the end portion, wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

Preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1a to e are schematic drawings illustrating a method of forming a waveguide structure embodying the present invention.

Figure 2 is a schematic drawing illustrating a method of coupling a waveguide structure to an optical fibre embodying the present invention.

Detailed Description of the Preferred Embodiment

In Figure 1a, a silicon wafer 10 is the starting substrate for subsequent thin film deposition of the various layers of the high optical confinement waveguide structure as described below.

Turning to Figure 1b, as a first step a silica buffer layer 12 is deposited on the silicon wafer 10 using Plasma Enhanced Chemical Vapour Deposition (PECVD) using a suitably oxidised silane precursor. The silica buffer layer 12 typically comprises a silicon dioxide, resulting in a refractive index of 1.46 (at 1.5 micro meter wavelength) of the buffer layer 12.

Next, as shown in Figure 1c, a waveguide layer 14 of amorphous silicon is deposited using again PECVD from a silane precursor.

It is noted that the refractive index of the resultant waveguide layer 14 can be adjusted from that of pure amorphous silicon (3.6 to 3.8 at 1.5 micro meter wavelength) to that of silicon dioxide (1.46 at 1.5 micro meter wavelength) by controlled oxidation of the silane during the PECVD process. This allows a great range of material properties of the waveguide layer 14, which in turn gives design flexibility for devices incorporating the high confinement optical waveguide.

In the next processing step, photolithography and reactive ion etching are used to produce a ridge 16 in the amorphous silicon layer which defines the high confinement optical waveguide. The height of the ridge 16 determines the degree of optical confinement, wherein the higher the ridge 16 is, the higher the optical confinement (see Figure 1d).

Finally, as illustrated in Figure 1e, a further silica layer 18 is deposited to form an outer cladding of the waveguide structure.

It will be appreciated by a person skilled in the art that the above described method allows control over various properties of the resultant high optical confinement waveguide structure.

Those include the control over the refractive index of the silicon-waveguide layer 14 as mentioned before, and the semiconductor properties of the silicon layer 14 (e.g. carrier lifetime which may be adjusted through suitable dopants). Furthermore, the thickness/height of the ridge 16 can be conveniently controlled, as well as the thickness and composition of the buffer layers 12 and 18.

The refractive index of the silicon layer 14 may further be altered through solid phase crystallisation of the deposited amorphous silicon layer 14 by eg. high temperature processing, including Rapid Thermal Annealing (RTA) or laser heating. It is noted here that the formation of grains caused by the crystallisation can cause an access scattering loss of the resultant waveguide. However, the grain size can be controlled independently by an appropriate doping of the silicon layer so that the high temperatures required to achieve the necessary re-crystallisation to eg. control the semiconductor properties of the silicon layer 12 do not lead to an excessive grain growth. In one embodiment, small amounts of oxygen can be incorporated during the deposition of the silicon layer 14, which can significantly restrain the grain growth even at temperatures in excess of 800ºC.

The above described method can for example be utilised to construct silicon-based thermo-optical

switches (TOS) and switching matrices. Despite the high thermo-optic coefficient of silicon it has so far been difficult to realise TOS, as in the SIMOX process little thermal isolation of the silicon waveguide from the highly thermally conductive silicon substrate could be achieved. This is a result of the small thickness of the barrier oxide layer formed from the implanted oxygen dictated by the SIMOX process.

In the embodiment of the present invention described above, the thickness of the silica buffer layer 12 can be varied conveniently in a sufficient thickness range as it utilises thin film technology rather than relying on implantation of oxygen into a substrate. Therefore, heat losses into the silicon substrate in TOS and switching matrices can be minimised, which in turn reduces the thermo-optical switching power required.

It will be appreciated by a person skilled in the art that the above described method can be utilised in the construction of other device structures, including for example devices which incorporate a processing element which is arranged to be controlled electrically to change its refractive index. Such processing elements can be useful in for example electro-optic modulator devices or phase shifter devices.

An advantage of another embodiment of the present invention will be described.

In silicon-based opto-electronics it is often required to couple light to and from an optical fibre. Typically, the coupling occurs at high loss due to optical mode mismatch between silica (fibre) and silicon material systems. One solution to this problem is to provide adiabatic tapering to the input/output silicon waveguides in order to expand their optical mode towards the optical

mode of fibres. However, this requires relatively large tapering distances to avoid radiation losses which partially negates the advantages of the compactness of the optical circuits as such.

Turning now to Figure 2, in an embodiment of the present invention a silicon waveguide 30 comprises a tapered end portion 32 for mode matching to an optical fibre 34 resting in a groove (not shown) of a carrier substrate 36. In this embodiment, controlled oxidation of the deposited amorphous silicon waveguide 30 is utilised to reduce the length of the required tapering 32. A laser beam 38 is scanned locally in the tapered end portion 32 of the amorphous silicon waveguide 30 to oxidise the amorphous silicon in that region, thereby reducing its refractive index in that region towards that of silica. This allows for a reduction in the length of the required tapering 32. In this embodiment, a CO_2 laser is used, but it will be appreciated that other lasers could be used to locally oxidise the amorphous silicon.

A refractive index profile in the tapered region 32 can be achieved by controlling the degree of oxidation, which will depend on the laser pulse frequency and exposure duration.

In another embodiment of the present invention, deposition of germanium-doped silicon waveguide layers can allow to introduce infrared absorption which in turn will allow incorporating a signal receive function in the waveguide. Accordingly, embodiments of the present invention can provide integrated active and passive circuit components.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific

embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprising" is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.

The claims defining the invention are

1. A method for forming a high optical confinement waveguide structure, the method comprising the step of:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate;

wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

2. A method as claimed in claim 1, further comprising the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in claims 2 or 3, wherein the first layer is silica-based.

5. A method as claimed in any one of the preceding claims, wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner such as to form a ridge structure in the deposited waveguide layer.

7. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure.

8. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide.

9. A method as claimed in claim 8, wherein the step of varying the refractive index comprises exposing the

deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

10. A method as claimed in any one of the preceding claims, wherein the silicon containing material comprises a dopant material.

11. A method as claimed in any one of the preceding claims, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

12. A method as claimed in claim 11, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

13. A method as claimed in any one of the preceding claims, wherein the method further comprises crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer.

14. A method as claimed in claim 13, wherein the step of crystallising comprises utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the silicon containing material to control a grain size in the crystallised waveguide.

15. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide comprises plasma enhanced chemical vapour deposition (PECVD).

16. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide comprises forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre.

17. A method as claimed in claim 16, wherein the step of forming the taper comprises varying the refractive

index of the deposited waveguide layer in the end portion of the waveguide.

18. A method as claimed in claim 17, wherein the varying of the refractive index in the end portion comprises controlled oxidation of the deposited waveguide layer.

19. A method as claimed in claim 18, wherein the controlled oxidation comprises a laser to heat the deposited waveguide layer.

20. A method as claimed in claim 19, wherein the laser comprises a CO_2 laser.

21. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

22. A method as claimed in claim 22, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

23. A method as claimed in claim 22, wherein the processing element is arranged to be controlled electrically to change its refractive index.

24. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of:

- oxidising the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling;

wherein the oxidising is controlled in a manner such that a refractive index profile is created in the end portion, and wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

25. An optical device incorporating a silicon-based waveguide structure on a substrate formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure.

Proposed Amended Claims

We claim:

~~The claims defining the invention are~~

1. A method for forming a high optical confinement waveguide structure, the method comprising the step of:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate;

wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

2. A method as claimed in claim 1, further comprising the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in claim~~s~~ 2 ~~or 3~~, wherein the first layer is silica-based.

5. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner such as to form a ridge structure in the deposited waveguide layer.

7. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the method further comprises the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure.

8. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the method further comprises the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide.

9. A method as claimed in claim 8, wherein the step of varying the refractive index comprises exposing the

deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

10. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the silicon containing material comprises a dopant material.

11. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

12. A method as claimed in claim 11, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

13. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the method further comprises crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer.

14. A method as claimed in claim 13, wherein the step of crystallising comprises utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the silicon containing material to control a grain size in the crystallised waveguide.

15. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the step of forming the waveguide comprises plasma enhanced chemical vapour deposition (PECVD).

16. A method as claimed in claim 1 ~~any one of the preceding claims~~, wherein the step of forming the waveguide comprises forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre.

17. A method as claimed in claim 16, wherein the step of forming the taper comprises varying the refractive

index of the deposited waveguide layer in the end portion of the waveguide.

18. A method as claimed in claim 17, wherein the varying of the refractive index in the end portion comprises controlled oxidation of the deposited waveguide layer.

19. A method as claimed in claim 18, wherein the controlled oxidation comprises a laser to heat the deposited waveguide layer.

20. A method as claimed in claim 19, wherein the laser comprises a CO_2 laser.

21. A method as claimed in ~~any one of the preceding claims~~ claim 1, wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

22. A method as claimed in claim 22, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

23. A method as claimed in claim 22, wherein the processing element is arranged to be controlled electrically to change its refractive index.

24. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of:

- oxidi~~z~~ing the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling;

wherein the oxidi~~z~~ing is controlled in a manner such that a refractive index profile is created in the end portion, and wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

25. An optical device incorporating a silicon-based waveguide structure on a substrate formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure.

PCT WORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) **International Patent Classification** 7 : G02B 6/13

A1

(11) **International Publication Number:** WO 00/57222

(43) **International Publication Date:** 28 September 2000 (28.09.00)

(21) **International Application Number:** PCT/AU00/00219

(22) **International Filing Date:** 20 March 2000 (20.03.00)

(30) **Priority Data:**
PP 9307 18 March 1999 (18.03.99) AU

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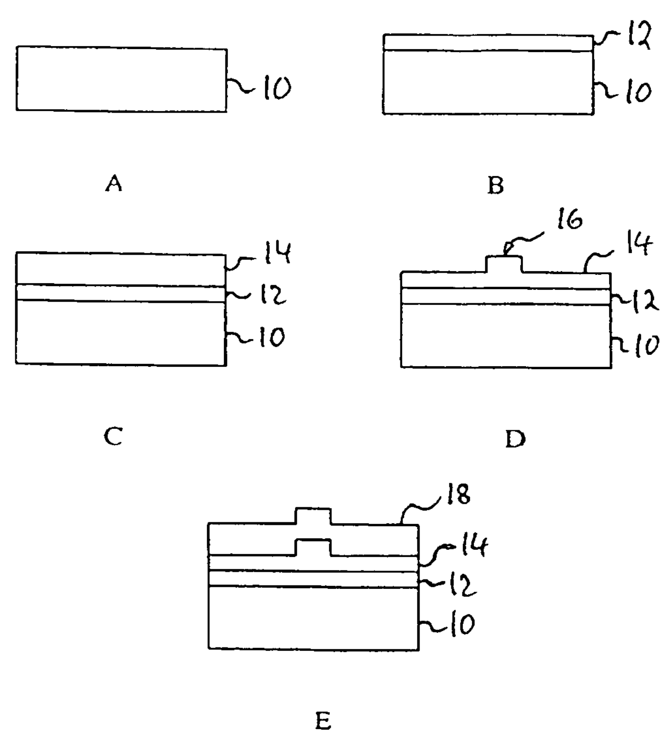
(81) **Designated States:** AU, CA, JP, KR, US, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE).

Published
With international search report.

(54) **Title:** WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

(57) **Abstract**

A method for forming a high optical confinement waveguide structure comprising the steps of: forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate; wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate; wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide structure such as to form a ridge structure in the deposited waveguide layer; wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.



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WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

Field of the Invention

The present invention relates broadly to a high optical confinement waveguide structure and a method for forming the same.

Background of the Invention

High confinement optical waveguides rely on a high refractive index contrast between the waveguide material and surrounding cladding material/optically isolating layers. This allows the design of very compact waveguide structures, which have found numerous applications enabling dramatic reduction in device dimensions while maintaining the required optical functionality.

Recently, silicon has been identified as a suitable material for the production of high confinement waveguide structures. Silicon has a high refractive index of the order of 4 at 1.5 micro meter wavelength. High confinement optical waveguides based on silicon as the waveguide material are presently manufactured utilising a technique known as "Separation by Implanted Oxygen" (SIMOX) to create Silicon on Insulator (SOI) structures. In the SIMOX technique oxygen is implanted into a silicon wafer. The wafer is then annealed to form a silicon layer above a layer of oxidised silicon formed from the implanted oxygen at a predetermined implantation depth.

However, this technique suffers from several disadvantages including the high cost related to the complex fabrication of SIMOX substrates, and the limited range of variations in the parameters of the SIMOX substrates, such as the limited range of the waveguide material properties (bulk silicon) and the limited range

of achievable thicknesses of the oxidised optical isolation layer created through oxygen implantation.

Summary of the Invention

The present invention provides a method for forming a high optical confinement waveguide structure. The method comprises the step of forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate, wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

Accordingly, thin film technology can be used to fabricate high optical confinement silicon-based waveguide structures, which can increase the range of properties of the silicon-based waveguide of the waveguide structure.

The method may further comprise the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer. The wafer may comprise a silicon wafer. The first layer may be silica-based.

The forming of the silicon-based waveguide may further comprise etching the deposited waveguide layer. The etching may be performed in a manner such as to form a ridge structure in the deposited waveguide layer. The method may further comprise the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure. Accordingly, the height of the ridge structure can be more accurately controlled compared to relying on uniformity of the etching process.

The method may further comprise the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide. The step

of varying the refractive index may comprise exposing the deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

The silicon containing material may comprise a dopant material.

The silicon containing material may be selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

The silicon containing material may be selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

The method may further comprise crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer. The step of crystallising may comprise utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the first material to control a grain size in the crystallised waveguide.

The step of forming the waveguide may comprise plasma enhanced chemical vapour deposition (PECVD).

The step of forming the waveguide may comprise forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre. The step of forming the taper may comprise varying the refractive index of the deposited waveguide layer in the end portion of the waveguide. The varying of the refractive index in the end portion may comprise controlled oxidation of the deposited waveguide layer. The controlled oxidation may comprise a laser to heat the deposited waveguide layer. The laser may comprise a CO_2 laser.

The method may further comprise the step of forming a processing element in and integrated with the deposited waveguide layer.

The present invention may alternatively be defined as providing an optical device incorporating a silicon-based waveguide structure formed on a substrate, and a processing element formed and integrated with the silicon-based waveguide structure.

The processing element may comprise a photodetector incorporating a dopant material in the silicon-based waveguide structure.

The present invention may alternatively be defined as providing a method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of oxidising the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling, wherein the oxidising is controlled in a manner such that a refractive index profile is created in the end portion, wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

Preferred forms of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1a to e are schematic drawings illustrating a method of forming a waveguide structure embodying the present invention.

Figure 2 is a schematic drawing illustrating a method of coupling a waveguide structure to an optical fibre embodying the present invention.

Detailed Description of the Preferred Embodiment

In Figure 1a, a silicon wafer 10 is the starting substrate for subsequent thin film deposition of the various layers of the high optical confinement waveguide structure as described below.

Turning to Figure 1b, as a first step a silica buffer layer 12 is deposited on the silicon wafer 10 using Plasma Enhanced Chemical Vapour Deposition (PECVD) using a suitably oxidised silane precursor. The silica buffer layer 12 typically comprises a silicon dioxide, resulting in a refractive index of 1.46 (at 1.5 micro meter wavelength) of the buffer layer 12.

Next, as shown in Figure 1c, a waveguide layer 14 of amorphous silicon is deposited using again PECVD from a silane precursor.

It is noted that the refractive index of the resultant waveguide layer 14 can be adjusted from that of pure amorphous silicon (3.6 to 3.8 at 1.5 micro meter wavelength) to that of silicon dioxide (1.46 at 1.5 micro meter wavelength) by controlled oxidation of the silane during the PECVD process. This allows a great range of material properties of the waveguide layer 14, which in turn gives design flexibility for devices incorporating the high confinement optical waveguide.

In the next processing step, photolithography and reactive ion etching are used to produce a ridge 16 in the amorphous silicon layer which defines the high confinement optical waveguide. The height of the ridge 16 determines the degree of optical confinement, wherein the higher the ridge 16 is, the higher the optical confinement (see Figure 1d).

Finally, as illustrated in Figure 1e, a further silica layer 18 is deposited to form an outer cladding of the waveguide structure.

It will be appreciated by a person skilled in the art that the above described method allows control over various properties of the resultant high optical confinement waveguide structure.

Those include the control over the refractive index of the silicon-waveguide layer 14 as mentioned before, and the semiconductor properties of the silicon layer 14 (e.g. carrier lifetime which may be adjusted through suitable dopants). Furthermore, the thickness/height of the ridge 16 can be conveniently controlled, as well as the thickness and composition of the buffer layers 12 and 18.

The refractive index of the silicon layer 14 may further be altered through solid phase crystallisation of the deposited amorphous silicon layer 14 by eg. high temperature processing, including Rapid Thermal Annealing (RTA) or laser heating. It is noted here that the formation of grains caused by the crystallisation can cause an access scattering loss of the resultant waveguide. However, the grain size can be controlled independently by an appropriate doping of the silicon layer so that the high temperatures required to achieve the necessary re-crystallisation to eg. control the semiconductor properties of the silicon layer 12 do not lead to an excessive grain growth. In one embodiment, small amounts of oxygen can be incorporated during the deposition of the silicon layer 14, which can significantly restrain the grain growth even at temperatures in excess of 800ºC.

The above described method can for example be utilised to construct silicon-based thermo-optical

switches (TOS) and switching matrices. Despite the high thermo-optic coefficient of silicon it has so far been difficult to realise TOS, as in the SIMOX process little thermal isolation of the silicon waveguide from the highly thermally conductive silicon substrate could be achieved. This is a result of the small thickness of the barrier oxide layer formed from the implanted oxygen dictated by the SIMOX process.

In the embodiment of the present invention described above, the thickness of the silica buffer layer 12 can be varied conveniently in a sufficient thickness range as it utilises thin film technology rather than relying on implantation of oxygen into a substrate. Therefore, heat losses into the silicon substrate in TOS and switching matrices can be minimised, which in turn reduces the thermo-optical switching power required.

It will be appreciated by a person skilled in the art that the above described method can be utilised in the construction of other device structures, including for example devices which incorporate a processing element which is arranged to be controlled electrically to change its refractive index. Such processing elements can be useful in for example electro-optic modulator devices or phase shifter devices.

An advantage of another embodiment of the present invention will be described.

In silicon-based opto-electronics it is often required to couple light to and from an optical fibre. Typically, the coupling occurs at high loss due to optical mode mismatch between silica (fibre) and silicon material systems. One solution to this problem is to provide adiabatic tapering to the input/output silicon waveguides in order to expand their optical mode towards the optical

mode of fibres. However, this requires relatively large tapering distances to avoid radiation losses which partially negates the advantages of the compactness of the optical circuits as such.

Turning now to Figure 2, in an embodiment of the present invention a silicon waveguide 30 comprises a tapered end portion 32 for mode matching to an optical fibre 34 resting in a groove (not shown) of a carrier substrate 36. In this embodiment, controlled oxidation of the deposited amorphous silicon waveguide 30 is utilised to reduce the length of the required tapering 32. A laser beam 38 is scanned locally in the tapered end portion 32 of the amorphous silicon waveguide 30 to oxidise the amorphous silicon in that region, thereby reducing its refractive index in that region towards that of silica. This allows for a reduction in the length of the required tapering 32. In this embodiment, a CO_2 laser is used, but it will be appreciated that other lasers could be used to locally oxidise the amorphous silicon.

A refractive index profile in the tapered region 32 can be achieved by controlling the degree of oxidation, which will depend on the laser pulse frequency and exposure duration.

In another embodiment of the present invention, deposition of germanium-doped silicon waveguide layers can allow to introduce infrared absorption which in turn will allow incorporating a signal receive function in the waveguide. Accordingly, embodiments of the present invention can provide integrated active and passive circuit components.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific

embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprising" is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.

The claims defining the invention are

1. A method for forming a high optical confinement waveguide structure, the method comprising the step of:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate;

wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

2. A method as claimed in claim 1, further comprising the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in claims 2 or 3, wherein the first layer is silica-based.

5. A method as claimed in any one of the preceding claims, wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner such as to form a ridge structure in the deposited waveguide layer.

7. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure.

8. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide.

9. A method as claimed in claim 8, wherein the step of varying the refractive index comprises exposing the

deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

10. A method as claimed in any one of the preceding claims, wherein the silicon containing material comprises a dopant material.

11. A method as claimed in any one of the preceding claims, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

12. A method as claimed in claim 11, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

13. A method as claimed in any one of the preceding claims, wherein the method further comprises crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer.

14. A method as claimed in claim 13, wherein the step of crystallising comprises utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the silicon containing material to control a grain size in the crystallised waveguide.

15. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide comprises plasma enhanced chemical vapour deposition (PECVD).

16. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide comprises forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre.

17. A method as claimed in claim 16, wherein the step of forming the taper comprises varying the refractive

index of the deposited waveguide layer in the end portion of the waveguide.

18. A method as claimed in claim 17, wherein the varying of the refractive index in the end portion comprises controlled oxidation of the deposited waveguide layer.

19. A method as claimed in claim 18, wherein the controlled oxidation comprises a laser to heat the deposited waveguide layer.

20. A method as claimed in claim 19, wherein the laser comprises a CO_2 laser.

21. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

22. A method as claimed in claim 22, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

23. A method as claimed in claim 22, wherein the processing element is arranged to be controlled electrically to change its refractive index.

24. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of:

- oxidising the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling;

wherein the oxidising is controlled in a manner such that a refractive index profile is created in the end portion, and wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

25. An optical device incorporating a silicon-based waveguide structure on a substrate formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure.

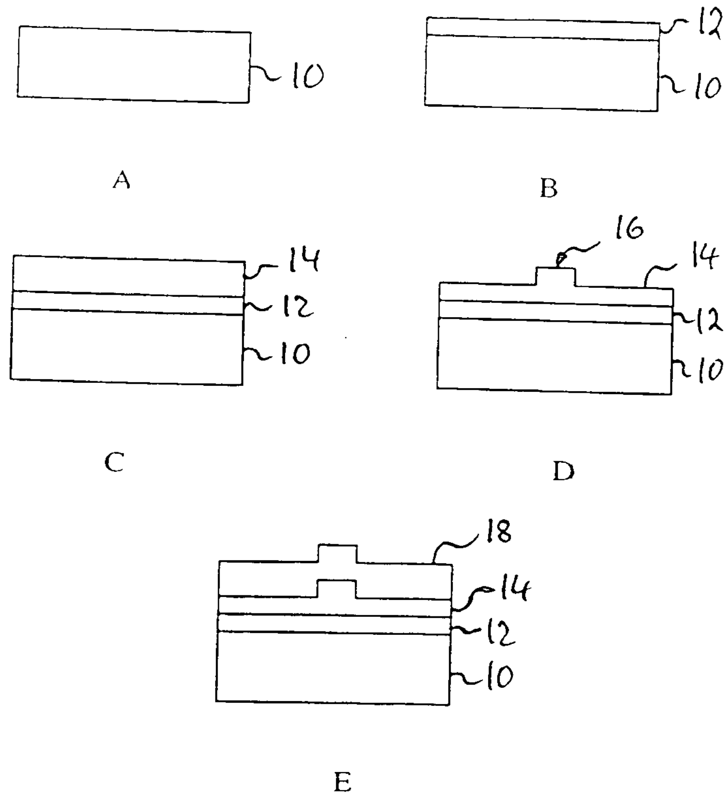

Figure 1

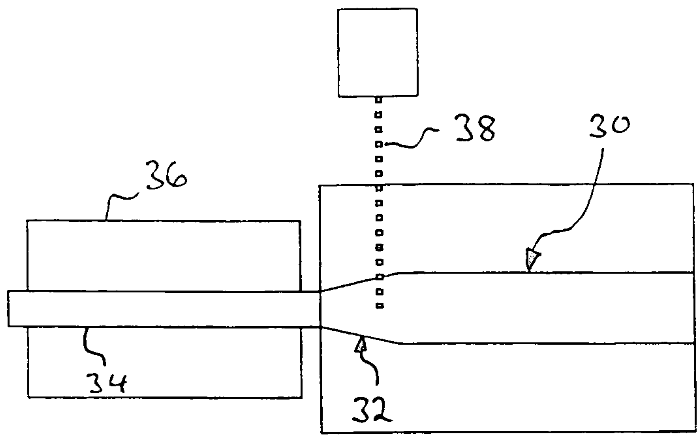

Figure 2

09/936775

REC'D 24 JUL 2001

WIPO	PCT

PATENT COOPERATION TREATY

PCT

INTERNATIONAL PRELIMINARY EXAMINATION REPORT

(PCT Article 36 and Rule 70)

Applicant's or agent's file reference FP12378	**FOR FURTHER ACTION** See Notification of Transmittal of International Preliminary Examination Report (Form PCT/IPEA/416).	
International Application No. **PCT/AU00/00219**	International Filing Date *(day/month/year)* 20 March 2000	Priority Date *(day/month/year)* 18 March 1999
International Patent Classification (IPC) or national classification and IPC **Int. Cl.** [7] G02B 6/13		
Applicant THE UNIVERSITY OF SYDNEY et al		

1. This international preliminary examination report has been prepared by this International Preliminary Examining Authority and is transmitted to the applicant according to Article 36.

2. This REPORT consists of a total of 4 sheets, including this cover sheet.

   [X] This report is also accompanied by ANNEXES, i.e., sheets of the description, claims and/or drawings which have been amended and are the basis for this report and/or sheets containing rectifications made before this Authority (see Rule 70.16 and Section 607 of the Administrative Instructions under the PCT).

   These annexes consist of a total of **13** sheet(s).

3. This report contains indications relating to the following items:

I	[X]	Basis of the report
II	[ ]	Priority
III	[ ]	Non-establishment of opinion with regard to novelty, inventive step and industrial applicability
IV	[X]	Lack of unity of invention
V	[X]	Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement
VI	[ ]	Certain documents cited
VII	[ ]	Certain defects in the international application
VIII	[ ]	Certain observations on the international application

Date of submission of the demand 18 October 2000	Date of completion of the report 13 July 2001
Name and mailing address of the IPEA/AU AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	Authorized Officer **LARS KOCH** Telephone No. (02) 6283 2551

I.	Basis of the report

1. With regard to the **elements** of the international application:*

- [ ] the international application as originally filed.
- [X] the description, pages , as originally filed,
  pages , filed with the demand,
  pages **1-9,** received on **5 July 2001** with the letter of **4 July 2001**
- [X] the claims, pages , as originally filed,
  pages , as amended (together with any statement) under Article 19,
  pages , filed with the demand,
  pages **10-13,** received on **5 July 2001** with the letter of **4 July 2001**
- [X] the drawings, pages **1/2-2/2,** as originally filed,
  pages , filed with the demand,
  pages , received on with the letter of
- [ ] the sequence listing part of the description:
  pages , as originally filed
  pages , filed with the demand
  pages , received on with the letter of

2. With regard to the **language**, all the elements marked above were available or furnished to this Authority in the language in which the international application was filed, unless otherwise indicated under this item.
These elements were available or furnished to this Authority in the following language which is:

- [ ] the language of a translation furnished for the purposes of international search (under Rule 23.1(b)).
- [ ] the language of publication of the international application (under Rule 48.3(b)).
- [ ] the language of the translation furnished for the purposes of international preliminary examination (under Rules 55.2 and/or 55.3).

3. With regard to any **nucleotide and/or amino acid sequence** disclosed in the international application, the international preliminary examination was carried out on the basis of the sequence listing:

- [ ] contained in the international application in written form.
- [ ] filed together with the international application in computer readable form.
- [ ] furnished subsequently to this Authority in written form.
- [ ] furnished subsequently to this Authority in computer readable form.
- [ ] The statement that the subsequently furnished written sequence listing does not go beyond the disclosure in the international application as filed has been furnished.
- [ ] The statement that the information recorded in computer readable form is identical to the written sequence listing has been furnished

4. [ ] The amendments have resulted in the cancellation of:

- [ ] the description, pages
- [ ] the claims, Nos.
- [ ] the drawings, sheets/fig.

5. [ ] This report has been established as if (some of) the amendments had not been made, since they have been considered to go beyond the disclosure as filed, as indicated in the Supplemental Box (Rule 70.2(c)).**

* *Replacement sheets which have been furnished to the receiving Office in response to an invitation under Article 14 are referred to in this report as "originally filed" and are not annexed to this report since they do not contain amendments (Rules 70.16 and 70.17).*

** *Any replacement sheet containing such amendments must be referred to under item 1 and annexed to this report*

IV.	Lack of unity of invention

1. In response to the invitation to restrict or pay additional fees the applicant has:

☐ restricted the claims.

☐ paid additional fees.

☐ paid additional fees under protest.

☐ neither restricted nor paid additional fees.

2. ☒ This Authority found that the requirement of unity of invention is not complied with and chose, according to Rule 68.1, not to invite the applicant to restrict or pay additional fees.

3. This Authority considers that the requirement of unity of invention in accordance with Rules 13.1, 13.2 and 13.3 is

☐ complied with.

☒ not complied with for the following reasons:

The application does not comply with the requirements of unity of invention because it does not relate to one invention or to a group of inventions so linked as to form a single general inventive concept. In coming to this conclusion, this Office has found that there are two inventions:

(1) Claims 1-19 and 21 are directed to a method for forming a silicon-based waveguide structure and a device incorporating the structure. It is considered that incorporation of amorphous silicon into the waveguide comprises a first "special technical feature".

(2) Claim 20 is directed to a method of optical coupling a silicon-based waveguide and an optical fibre. It is considered that a controllable oxidation of the silicon waveguide in order to alter the refractive index of an end portion of the waveguide comprises a second "special technical feature".

The feature common to all of the claims is silicon-based waveguide. However this common feature is generic in the art. Consequently the common feature does not constitute "a special technical feature" since it makes no contribution over the prior art. Since there exists no other common feature which can be considered as a special technical feature, a "technical relationship" between the inventions, as defined in PCT rule 13.2 does not exist. Consequently it appears that, **a posteriori**, the claims do not satisfy the requirement that they relate to one invention only.

4. Consequently, the following parts of the international application were the subject of international preliminary examination in establishing this report:

☒ all parts.

☐ the parts relating to claims Nos.

V. Reasoned statement under Article 35(2) with regard to novelty, inventive step or industrial applicability; citations and explanations supporting such statement

1. Statement

Novelty (N)	Claims **2-6, 8, 11-20**	**YES**
	Claims **1, 7, 9, 10, 21**	**NO**
Inventive step (IS)	Claims **11, 15-20**	**YES**
	Claims **1-10, 12-14, 21**	**NO**
Industrial applicability (IA)	Claims **1-21**	**YES**
	Claims	**NO**

2. Citations and explanations (Rule 70.7)

New citations raised:

D11 US 4695122 A (ISHIDA *et al.*) 22 September 1987

D12 US 5515460 A (STONE) 7 May 1996

NOVELTY (N): claims 1, 7, 9, 10, 21

Claims 1, 7, 9, 10:

The document D11 discloses all the essential features of the claims 1, 7, 9 and 10. In particular, it discloses an optical waveguide of an amorphous silicon formed on a quartz glass substrate by carrying out a sputtering operation (see abstract, col. 2 lines 37-40, and Embodiment 3). The refractive index of the amorphous silicon layer has been controllably varied by introducing the dopants (hydrogen, nitrogen or oxygen) into the layer during the sputtering operation (see col. 2 line 65 - col. 3 line 17 and figure 4).

Claim 21:

The document D12 discloses all the essential features of claim 21. In particular, it discloses an optical device including a silicon-based waveguide structure which incorporates an amorphous-silicon-based layer (see abstract, col. 1 lines 63-66 and figures 2, 3), and a processing element (a tunable multiplexer) integrated with the structure (see claims 1-3).

INVENTIVE STEP (IS): claims 1-10, 12-14, 21

Claims 1, 7, 9, 10, 21: as above

Claims 2-6, 8:

The features added by the dependent claims 2-6 and 8 represent the routine technical procedures in the art.

Claims 12-14:

An obvious combination of D11 and D7 (US 4886538) discloses all the essential features of claims 12-14. In particular, a controllable variation of the refractive index of the amorphous silicon layer via incorporation of oxygen in the layer in order to gradually decrease the refractive index to that of silica (about 1.46) is disclosed in D11 (see col. 3 lines 2-8), whereas a tapering of the waveguide layer as well as controlled variation in its refractive index in order to achieve low-loss optical coupling to an optical fibre is disclosed in D7 (see col. 1 lines 44-51 and 54-66).

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WAVEGUIDE STRUCTURE AND METHOD OF FORMING THE WAVEGUIDE STRUCTURE

Field of the Invention

The present invention relates broadly to a high-optical-confinement waveguide structure and a method for forming the same.

Background of the Invention

High-confinement optical waveguides rely on a high refractive index contrast between the waveguide material and surrounding cladding material/optically isolating layers. This allows the design of very compact waveguide structures, which have found numerous applications enabling dramatic reduction in device dimensions while maintaining the required optical functionality.

Recently, silicon has been identified as a suitable material for the production of high confinement waveguide structures. Silicon has a high refractive index of the order of 4 at 1.5 a wavelength of about 1.5 μm. High confinement optical waveguides based on silicon as the waveguide core material are presently manufactured utilising a technique known as "Separation by Implanted Oxygen" (SIMOX) to create Silicon on Insulator (SOI) structures. In the SIMOX technique, oxygen is implanted into a silicon wafer. The wafer is then annealed to form a silicon layer above a layer of oxidised silicon formed from the implanted oxygen at a predetermined implantation depth.

However, this technique suffers from several disadvantages including the high cost related to the

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complex fabrication of SIMOX substrates, and the limited range of variations in the parameters of the SIMOX substrates, such as the limited range of the waveguide material properties (bulk silicon) and the limited range of achievable thicknesses of the oxidised optical isolation layer created through oxygen implantation.

Summary of the Invention

The present invention provides a method for forming a high-optical-confinement waveguide structure, the method comprising:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer comprising amorphous silicon onto the substrate;

wherein the waveguide layer has a refractive index which is greater than a refractive index of the substrate.

Accordingly, thin film technology can be used to fabricate high optical confinement silicon-based waveguide structures, which can increase the range of properties of the silicon-based waveguide of the waveguide structure.

The method may further comprise a step of depositing a first layer of a first material on a wafer so as to form the substrate prior to depositing the waveguide layer. The wafer may comprise a silicon wafer. The first layer may be silica-based.

The step of forming the silicon-based waveguide may further comprise etching the deposited waveguide layer. The etching may be performed in a manner which forms a ridge structure in the deposited waveguide layer. The method may further comprise a step of depositing a second layer of a second material so as to form an etch-stop, whereby to enable the formation of the ridge structure. Accordingly, the height of the ridge structure can be more

accurately controlled compared to relying on uniformity of the etching process.

The method may further comprise a step of creating a refractive index variation in the deposited waveguide layer so as to form a non-constant refractive index profile in the waveguide layer. The step of creating the refractive index variation may comprise exposing the deposited waveguide layer to radiation so as to induce refractive index changes in the deposited waveguide layer.

The waveguide layer may further comprise a dopant material.

The deposited waveguide layer may further comprise at least partially-oxidised silicon.

The method may further comprise crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer. The step of crystallising may comprise utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the first material to control a grain size in the crystallised waveguide.

The waveguide may be deposited by plasma enhanced chemical vapour deposition (PECVD).

The step of forming the waveguide may further comprise forming a taper in an end portion of the deposited waveguide layer for facilitating optical coupling to an optical fibre. The step of forming the waveguide further comprises creating a variation of refractive index of the deposited waveguide layer in the end portion of the waveguide. The step of creating the variation of the refractive index in the end portion may comprise carrying out controlled oxidation of the end portion. The controlled oxidation may comprise using a

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laser to heat the deposited waveguide layer. The laser may comprise a CO_2 laser.

The method may further comprise a step of forming a processing element in and integrated with the deposited waveguide layer.

The present invention may alternatively be defined as an optical device incorporating a silicon-based waveguide structure formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure, wherein the silicon-based waveguide structure incorporates an amorphous-silicon-based waveguide layer.

The processing element may comprise a photodetector incorporating a dopant material in the silicon-based waveguide structure.

The present invention may alternatively be defined as providing a method of coupling a silicon-based waveguide to an optical fibre, the method comprising: - oxidising the silicon-based waveguide in an end portion thereof so as to alter a refractive index of the end portion; wherein the end portion is arranged to facilitate optical coupling of the waveguide to an end of an optical fibre, the oxidation being controlled so as to create a refractive index profile in which the refractive index at an outer end of the end portion matches that of the optical fibre.

Embodiments of the invention will now be described, by way of example only, with reference to the accompanying drawings, in which:

Brief Description of the Drawings

Figure 1a to e are schematic drawings illustrating a method of forming a waveguide structure embodying the present invention.

Figure 2 is a schematic drawing illustrating a method of coupling a waveguide structure to an optical fibre embodying the present invention.

Detailed Description of the Preferred Embodiment

In Figure 1a, a silicon wafer 10 is the starting substrate for subsequent thin film deposition of the various layers of the high optical confinement waveguide structure as described below.

Turning to Figure 1b, as a first step a silica buffer layer 12 is deposited on the silicon wafer 10 using Plasma Enhanced Chemical Vapour Deposition (PECVD) using a suitably oxidised silane precursor. The silica buffer layer 12 typically comprises a silicon dioxide, resulting in a refractive index of 1.46 (at 1.5 micro meter wavelength) of the buffer layer 12.

Next, as shown in Figure 1c, a waveguide layer 14 of amorphous silicon is deposited using again PECVD from a silane precursor.

It is noted that the refractive index of the resultant waveguide layer 14 can be adjusted from that of pure amorphous silicon (3.6 to 3.8 at a wavelength of 1.5 μm) to that of silicon dioxide (1.46 at wavelength of 1.5 μm) by controlled oxidation of the silane during the PECVD process. This allows a great range of material properties of the waveguide layer 14, which in turn gives design flexibility for devices incorporating the high confinement optical waveguide.

In the next processing step, photolithography and reactive ion etching are used to produce a ridge 16 in the amorphous silicon layer which defines the high confinement

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optical waveguide. The height of the ridge 16 determines the degree of optical confinement, wherein the higher the ridge 16 is, the higher the optical confinement (see Figure 1d).

Finally, as illustrated in Figure 1e, a further silica layer 18 is deposited to form an outer cladding of the waveguide structure.

It will be appreciated by a person skilled in the art that the above described method allows control over various properties of the resultant high optical confinement waveguide structure.

Those include the control over the refractive index of the silicon-waveguide layer 14 as mentioned before, and the semiconductor properties of the silicon layer 14 (e.g. carrier lifetime which may be adjusted through suitable dopants). Furthermore, the thickness/height of the ridge 16 can be conveniently controlled, as well as the thickness and composition of the buffer layers 12 and 18.

The refractive index of the silicon layer 14 may further be altered through solid phase crystallisation of the deposited amorphous silicon layer 14 by high temperature processing, such as rapid thermal annealing (RTA) or laser heating. It is noted here that the formation of grains caused by the crystallisation can cause an access scattering loss of the resultant waveguide. However, the grain size can be controlled independently by an appropriate doping of the silicon layer so that the high temperatures required to achieve the necessary re-crystallisation to eg. control the semiconductor properties of the silicon layer 12 do not lead to an excessive grain growth. In one embodiment,

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small amounts of oxygen can be incorporated during the deposition of the silicon layer 14, which can significantly restrain the grain growth even at temperatures in excess of 800ºC.

The above described method can for example be utilised to construct silicon-based thermo-optical switches (TOS) and switching matrices. Despite the high thermo-optic coefficient of silicon it has so far been difficult to realise TOS, as in the SIMOX process little thermal isolation of the silicon waveguide from the highly thermally conductive silicon substrate could be achieved. This is a result of the small thickness of the barrier oxide layer formed from the implanted oxygen dictated by the SIMOX process.

In the embodiment of the present invention described above, the thickness of the silica buffer layer 12 can be varied conveniently in a sufficient thickness range as it utilises thin film technology rather than relying on implantation of oxygen into a substrate. Therefore, heat losses into the silicon substrate in TOS and switching matrices can be minimised, which in turn reduces the thermo-optical switching power required.

It will be appreciated by a person skilled in the art that the above described method can be utilised in the construction of other device structures, including for example devices which incorporate a processing element which is arranged to be controlled electrically to change its refractive index. Such processing elements can be useful in for example electro-optic modulator devices or phase shifter devices.

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An advantage of another embodiment of the present invention will be described.

In silicon-based opto-electronics it is often required to couple light to and from an optical fibre. Typically, the coupling losses are high due to an optical mode mismatch between silica (fibre) and silicon systems. One solution to this problem is to provide adiabatic tapering to the input/output silicon waveguides in order to expand their optical mode towards the optical mode of the fibres. However, this requires relatively large tapering distances to avoid radiation losses which partially negates the advantages of the compactness of the optical circuits as such.

Turning now to Figure 2, in an embodiment of the present invention a silicon waveguide 30 comprises a tapered end portion 32 for mode matching to an optical fibre 34 resting in a groove (not shown) of a carrier substrate 36. In this embodiment, controlled oxidation of the deposited amorphous silicon waveguide 30 is utilised to reduce the length of the required tapering 32. A laser beam 38 is scanned locally in the tapered end portion 32 of the amorphous silicon waveguide 30 to oxidise the amorphous silicon in that region, thereby reducing its refractive index in that region towards that of silica. This allows for a reduction in the length of the required tapering 32. In this embodiment, a CO_2 laser is used, but it will be appreciated that other lasers could be used to locally oxidise the amorphous silicon.

A refractive index profile in the tapered region 32 can be achieved by controlling the degree of oxidation, which will depend on the laser pulse frequency and exposure duration.

In another embodiment of the present invention, deposition of germanium-doped silicon waveguide layers can introduce infrared absorption which in turn will allow incorporating a signal receive function in the waveguide. Accordingly, embodiments of the present invention can provide integrated active and passive circuit components.

It will be appreciated by a person skilled in the art that numerous variations and/or modifications may be made to the present invention as shown in the specific embodiments without departing from the spirit or scope of the invention as broadly described. The present embodiments are, therefore, to be considered in all respects to be illustrative and not restrictive.

In the claims that follow and in the summary of the invention, except where the context requires otherwise due to express language or necessary implication, the word "comprising" is used in the sense of "including", i.e. the features specified may be associated with further features in various embodiments of the invention.

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THE CLAIMS

1. A method for forming a high-optical-confinement waveguide structure, the method comprising:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer comprising amorphous silicon onto the substrate;

wherein the waveguide layer has a refractive index which is greater than a refractive index of the substrate.

2. A method as claimed in claim 1, further comprising a step of depositing a first layer of a first material on a wafer so as to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in either claim 2 or 3, wherein the first layer is silica-based.

5. A method as claimed in any one of the preceding claims, wherein the step of forming the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner which forms a ridge structure in the deposited waveguide layer.

7. A method as claimed in any one of the preceding claims, wherein the method further comprises a step of

creating a refractive index variation in the deposited waveguide layer so as to form a non-constant refractive index profile in the waveguide layer.

8. A method as claimed in claim 7, wherein the step of creating the refractive index variation comprises exposing the deposited waveguide layer to radiation so as to induce refractive index changes in the deposited waveguide layer.

9. A method as claimed in any one of the preceding claims, wherein the waveguide layer further comprises a dopant material.

10. A method as claimed in any one of the preceding claims, wherein the deposited waveguide layer further comprises at least partially-oxidised silicon.

11. A method as claimed in any one of the preceding claims, wherein waveguide layer is deposited by plasma-enhanced chemical vapour deposition (PECVD).

12. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide further comprises forming a taper in an end portion of the deposited waveguide layer for facilitating optical coupling to an optical fibre.

13. A method as claimed in claim 12, wherein the step of forming waveguide further comprises creating a variation of refractive index of the deposited waveguide layer in the end portion of the waveguide.

14. A method as claimed in claim 13, wherein the step of creating the variation of refractive index in the end portion comprises carrying out controlled oxidation of the end portion.

15. A method as claimed in claim 14, wherein the controlled oxidation comprises using a laser to heat the deposited waveguide layer.

16. A method as claimed in claim 15, wherein the laser comprises a CO_2 laser.

17. A method as claimed in any one of the preceding claims, wherein the method further comprises a step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

18. A method as claimed in claim 17, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

19. A method as claimed in claim 18, wherein the processing element is arranged to be controlled electrically to change its refractive index.

20. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising:

- oxidising the silicon-based waveguide in an end portion thereof so as to alter a refractive index of the end portion; wherein the end portion is arranged to facilitate optical coupling of the waveguide to an end of

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an optical fibre, the oxidation being controlled so as to create a refractive index profile in which the refractive index at an outer end of the end portion matches that of the optical fibre.

21. An optical device incorporating a silicon-based waveguide structure formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure, wherein the silicon-based waveguide structure incorporates an amorphous-silicon-based waveguide layer.

INTERNATIONAL SEARCH REPORT

International application No
PCT/AU00/00219

A. CLASSIFICATION OF SUBJECT MATTER

Int. Cl: G02B 6/13

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)
IPC G02B/IC G02F/IC H01L/IC

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)
DWPI, JAPIO

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
	US 5 841 931 A (FORESI et al.) 24 November 1998	
X	See whole document	1-8, 10-13, 15, 21, 25
Y		9, 16-20, 22-24
	US 5 757 986 A (CRAMPTON et al.) 26 May 1998	
X	See whole document	1-8, 10, 21, 25
Y		9, 11-13, 15-20, 22-24
	GB 2 323 450 A (UK SEC FOR DEFENCE) 23 September 1998	
X	See whole document	1-8, 10, 21, 25
Y		9, 11-13, 15-20, 22-24

[X] Further documents are listed in the continuation of Box C [X] See patent family annex

* Special categories of cited documents:

"A" document defining the general state of the art which is not considered to be of particular relevance

"E" earlier application or patent but published on or after the international filing date

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"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone

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Date of the actual completion of the international search	Date of mailing of the international search report
19 May 2000	16 JUN 2000

Name and mailing address of the ISA/AU	Authorized officer
AUSTRALIAN PATENT OFFICE PO BOX 200, WODEN ACT 2606, AUSTRALIA E-mail address: pct@ipaustralia.gov.au Facsimile No. (02) 6285 3929	DEAN ALLE Telephone No : (02) 6283 2286

INTERNATIONAL SEARCH REPORT

International application No.
PCT/AU00/00219

C (Continuation). DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No
X Y	US 5 838 870 A (SOREF) 17 November 1998 See whole document	1-8 ,10 ,21 ,25 9, 11-13, 15-20, 22-24
X Y	US 4 997 246 A (MAY et al.) 5 March 1991 See whole document	1, 8, 10, 21, 25 9, 11-13, 15-20, 22-24
X Y	US 4 787 691 A (LORENZO et al.) 29 November 1988 See whole document	1, 8, 10, 21, 25 9, 11-13, 15-20, 22-24
Y	US 4 886 538 A (MAHAPATRA) 12 December 1989 See whole document	16-20, 24
Y	US 5 657 338 A (KITAMURA) 12 August 1997 See whole document	16
P,X	US 6 003 222 A (BARBAROSSA) 21 December 1999 See whole document	1-5, 8,10, 16-18
Y	WO 97/09645 A1 (UNISEARCH LIMITED) 13 March 1997 See whole document	1-13, 15-20
X Y	WO 96/33429 A1 (UNISEARCH LIMITED) 24 October 1996 See whole document	1-8, 10-13, 15, 21, 25 9, 16-20, 22-24

INTERNATIONAL SEARCH REPORT
Information on patent family members

International application No.
PCT/AU00/00219

This Annex lists the known "A" publication level patent family members relating to the patent documents cited in the above-mentioned international search report. The Australian Patent Office is in no way liable for these particulars which are merely given for the purpose of information.

Patent Document Cited in Search Report		Patent Family Member					
US	5841931	NONE					
US	5757986	WO	9508787	EP	720754	US	5908305
GB	2323450	GB	2337132	WO	9843128		
US	5838870	NONE					
US	4997246	EP	433552	JP	3196120		
US	4787691	NONE					
US	4886538	CA	1323194	EP	302043	JP	1049004
US	5657338	JP	8125279	US	5792674		
US	6003222	EP	890850	JP	11084156	JP	8125279
		US	5657338	US	5792674		
WO	9709645	AU	67830/96	CA	2231373	EP	871910
WO	9633429	AU	41112/96	CA	2218854	EP	821799

END OF ANNEX

The claims defining the invention are

1. A method for forming a high optical confinement waveguide structure, the method comprising the step of:

- forming a silicon-based waveguide on a substrate by depositing a waveguide layer of silicon containing material onto the substrate;

wherein the material is selected in a manner such that the refractive index of the waveguide is greater than the refractive index of the substrate.

2. A method as claimed in claim 1, further comprising the step of depositing a first layer of a first material on a wafer to form the substrate prior to depositing the waveguide layer.

3. A method as claimed in claim 2, wherein the wafer comprises a silicon wafer.

4. A method as claimed in claims 2 or 3, wherein the first layer is silica-based.

5. A method as claimed in any one of the preceding claims, wherein the forming of the silicon-based waveguide further comprises etching the deposited waveguide layer.

6. A method as claimed in claim 5, wherein the etching is performed in a manner such as to form a ridge structure in the deposited waveguide layer.

7. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of depositing a second layer of a second material to form an etch-stop during the etching of the ridge structure.

8. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of varying the refractive index in the deposited waveguide layer to form a refractive index profile in the waveguide.

9. A method as claimed in claim 8, wherein the step of varying the refractive index comprises exposing the

deposited waveguide layer to radiation to induce refractive index changes in the deposited waveguide layer.

10. A method as claimed in any one of the preceding claims, wherein the silicon containing material comprises a dopant material.

11. A method as claimed in any one of the preceding claims, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon.

12. A method as claimed in claim 11, wherein the silicon containing material is selected in a manner such that the deposited waveguide layer comprises amorphous silicon and oxidised silicon.

13. A method as claimed in any one of the preceding claims, wherein the method further comprises crystallising the deposited waveguide layer and forming the waveguide in the polycrystalline waveguide layer.

14. A method as claimed in claim 13, wherein the step of crystallising comprises utilising a dopant incorporated into the waveguide during the deposition of the waveguide layer in the silicon containing material to control a grain size in the crystallised waveguide.

15. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide comprises plasma enhanced chemical vapour deposition (PECVD).

16. A method as claimed in any one of the preceding claims, wherein the step of forming the waveguide comprises forming a taper in an end portion of the deposited waveguide for optical coupling to an optical fibre.

17. A method as claimed in claim 16, wherein the step of forming the taper comprises varying the refractive

index of the deposited waveguide layer in the end portion of the waveguide.

18. A method as claimed in claim 17, wherein the varying of the refractive index in the end portion comprises controlled oxidation of the deposited waveguide layer.

19. A method as claimed in claim 18, wherein the controlled oxidation comprises a laser to heat the deposited waveguide layer.

20. A method as claimed in claim 19, wherein the laser comprises a CO_2 laser.

21. A method as claimed in any one of the preceding claims, wherein the method further comprises the step of forming an optical signal processing element in and integrated with the deposited waveguide layer.

22. A method as claimed in claim 22, wherein the processing element comprises a photodetector incorporating a dopant material in the silicon-based waveguide structure.

23. A method as claimed in claim 22, wherein the processing element is arranged to be controlled electrically to change its refractive index.

24. A method of coupling a silicon-based waveguide to an optical fibre, the method comprising the steps of:

- oxidising the silicon-based waveguide in an end portion thereof, the end portion being, in use, located adjacent an end phase of the optical fibre for optical coupling;

wherein the oxidising is controlled in a manner such that a refractive index profile is created in the end portion, and wherein the refractive index is altered in a manner such that it substantially matches that of the optical fibre at an outer end of the end portion.

25. An optical device incorporating a silicon-based waveguide structure on a substrate formed on a substrate, the device comprising a processing element formed and integrated with the silicon-based waveguide structure.

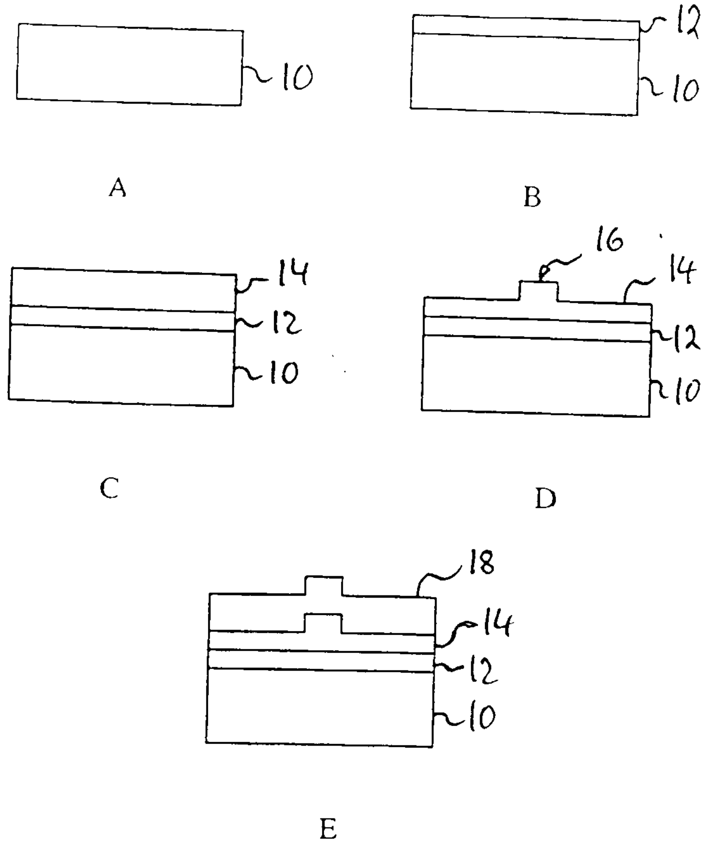

Figure 1

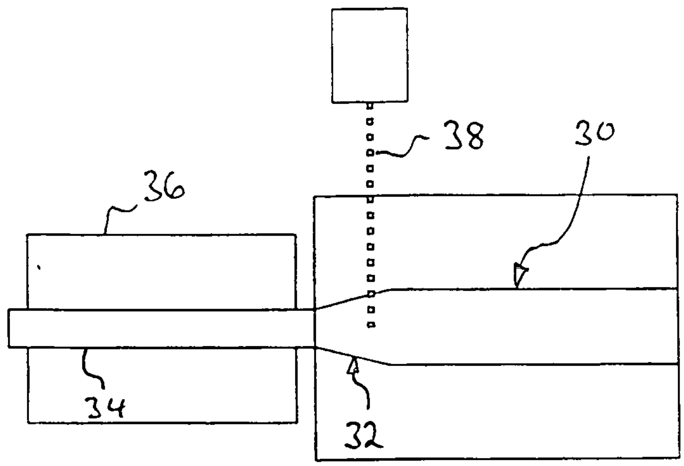

Figure 2

ATENT COOPERATION TRE Y

From the INTERNATIONAL BUREAU

PCT

NOTIFICATION OF ELECTION

(PCT Rule 61.2)

To:

Commissioner
US Department of Commerce
United States Patent and Trademark Office, PCT
2011 South Clark Place Room CP2/5C24
Arlington, VA 22202
ETATS-UNIS D'AMERIQUE

in its capacity as elected Office

Date of mailing (day/month/year) 02 November 2000 (02.11.00)	
International application No. PCT/AU00/00219	**Applicant's or agent's file reference** MHK:IHA:FP12378
International filing date (day/month/year) 20 March 2000 (20.03.00)	**Priority date** (day/month/year) 18 March 1999 (18.03.99)
Applicant BAZYLENKO, Michael et al	

1. The designated Office is hereby notified of its election made:

   ☒ in the demand filed with the International Preliminary Examining Authority on:

   18 October 2000 (18.10.00)

   ☐ in a notice effecting later election filed with the International Bureau on:

2. The election ☒ was ☐ was not

   made before the expiration of 19 months from the priority date or, where Rule 32 applies, within the time limit under Rule 32.2(b).

The International Bureau of WIPO **34, chemin des Colombettes** **1211 Geneva 20, Switzerland** Facsimile No.: (41-22) 740.14.35	Authorized officer F. Baechler Telephone No.: (41-22) 338.83.38